Scientific Justification

The Hubble diagram for Type Ia supernovae (SNe Ia), extended to redshifts well beyond $z = 0.25$ (Fig. 1), provides perhaps the most direct current measurement of the expansion history of the universe—and hence the most direct evidence for an accelerating expansion. Our collaboration team has developed an approach to this measurement that resulted in a determination, based on 42 SNe at $0.18 < z < 0.83$, of $\Omega_M = 0.28^{+0.09}_{-0.08}$ for a flat universe (Perlmutter et al. 1999, see also Riess et al. 1998). This evidence has been increasingly strengthened, both by tests and improvements of the supernova measurements and by independent, cross-cutting cosmological measurements. In particular the recent balloon-based CMB measurement (Jaffe et al. 2000) strongly indicate that the geometry of the universe is flat, reinforcing evidence for an accelerating universe by eliminating the possibility of a low-density open universe (Fig. 2a). There are now two important directions to pursue in this proposal:

(1) Extending and Filling a SN Ia Hubble Diagram to $z \sim 1.2$.

We currently have the opportunity to obtain a Hubble diagram of long lasting value as a record of the expansion history of the universe over the last 10 billion years. Significant improvements are now being made in the systematic uncertainties in SN measurements, and it is therefore now useful to reduce the statistical uncertainty by almost a factor of two — that is, by studying an additional ~100 SNe Ia. This is a key task, and we are therefore proposing a concerted effort to discover and study 15 SNe Ia. The wide-field capabilities of the Suprime-Cam on Subaru are crucial to discover these SNe.

This Hubble diagram redshift range that we propose to populate is aimed at addressing several of the more important scientific questions of our day. First, it allows a determination of the curvature of the universe and decoupled measurements of Ω_M and Ω_Λ: SNe Ia beyond $z \sim 0.85$ can dramatically shorten the major-axis of the current Ω_M—Ω_Λ error ellipse (cf. Goobar & Perlmutter 1995 and Fig. 2). After our proposed observations, $\Omega_\Lambda = 0$ could be ruled out at better than 3σ. For a flat universe, Ω_M and Ω_Λ could be constrained to $\sim 7\%$. The resulting estimate of Ω_M, for *any* Ω_Λ, is still accurate to ±0.2 in this simulation and would be a first check on the CMB measurements that indicate a flat geometry.

Second, the Hubble diagram out to $z \sim 1$ provides one of the only known ways to constrain the physics of "dark energy" that apparently is accelerating the universe's expansion — by measuring its equation-of-state ratio, $w \equiv p/\rho$. The current constraints on w are consistent with a very wide range of dark energy theories, including a Cosmological Constant ($w = -1$) (Perlmutter et al. 1999, Garnavich et al. 1998); the proposed data set, together with data now being analyzed can tighten these constraints by 40%, potentially ruling out several contending theories. Dark energy theories can be further differentiated on the Hubble diagram at $0.3 \lesssim z \lesssim 1$ by their behavior *over the range* of z (Astier 2000).

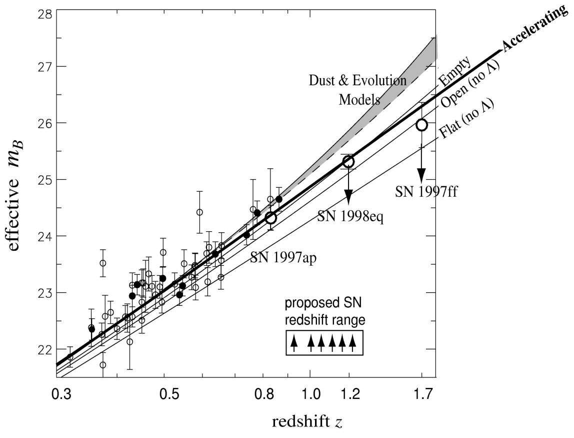

Figure 1: Open points show Hubble diagram for 42 high-z SNe (Perlmutter *et al.* 1999) along with comparable non-host-extinction-corrected points (filled circles) for our more recently discovered SNe with HST followup (Knop *et al.* 2000, 2002). The magnitude difference between the best-fit "Accelerating (Λ)" world model $(\Omega_M, \Omega_\Lambda)$ =(0.28, 0.72) and suitable ones with Ω_Λ=0 show redshift dependencies which would be very hard to mimic within the context of SN evolution or grey dust hypotheses (the grey shaded region is an example model with uniform dust). By extending our survey beyond z=1, the *shape* of the Hubble diagram alone would become sufficient evidence to support a cosmological constant.

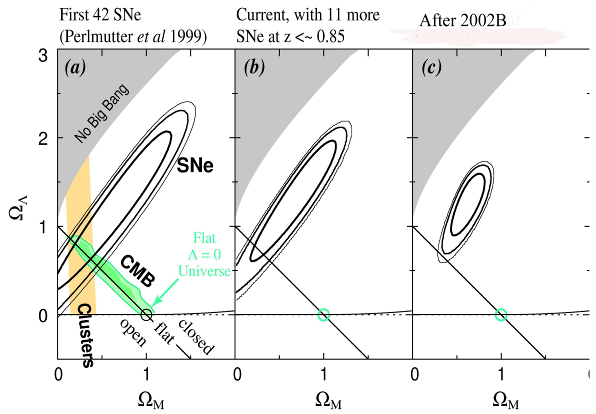

Figure 2: 68%, 90% and 99% confidence contours in the $(\Omega_M, \Omega_\Lambda)$ plane from the present 42 high-z Sne from Perlmutter *et al.* Also show are the recent results from Jaffe *et al* using CMB anisotropies and constraints from galaxy clusters. (b) with the 11 already collected SNe at $z < 0.85$. (c) : the estimated effect of adding the data available after the proposed campaign. These simulations show that we can check the CMB curvature measurements; we emphasize this by using a non-flat scenario, e.g. using the central $(\Omega_M, \Omega_\Lambda)$ values of panel (a).

Using SUBARU (Suprime-Cam/FOCAS) we found 7 distant SNe (including two at $z > 1$) in 2001 spring (Doi et al. 2001), and one at $z = 0.93$ was photometrically followed with HST. The search run in spring 2002 is currently undergoing, and we have found more than 10 SNe found with Surpiem-Cam and spectroscopically followed with SUBARU/FOCAS, VLT/FORS2, GEMINI/GMOS and KECK/ESI. Thee distant SNe ($z = 1.08, 1.06$, and 0.88) found with Suprime-Cam are now being observed with HST. Suprime-Cam starts playing the key role to find most distant SNe, and an imaging survey as a part of the "Big Project" will guarantee us those valuable targets in this fall. In Fig. 3 - Fig. 6, we showed images and a spectrum of a SNe which is recently (Apr., 2002) found with Suprime-Cam, spectroscopically observed with FOCAS, and being photometrically followed with VLT/ISAAC and with HST.

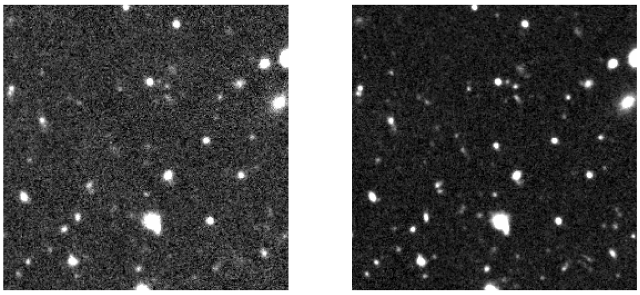

Figure 3: Suprime-Cam i'-band images of a distant SN (temperary name S02-032) on Mar.17, 2002 (left) and on Apr.8, 2002 (right). Clear increase of the SN light can be seen in the center of the right panel.

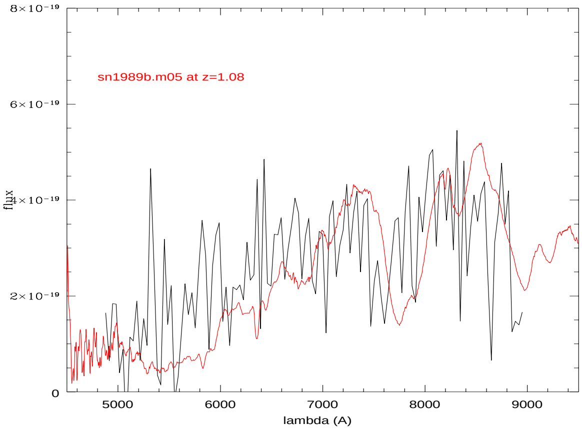

Figure 4: A spectrum of S02-032 taken with FOCAS (preliminary results from 1-hour exposure data). A spectrum of nearby SN Ia (5 days before miximum brightness) was superposed (red line).

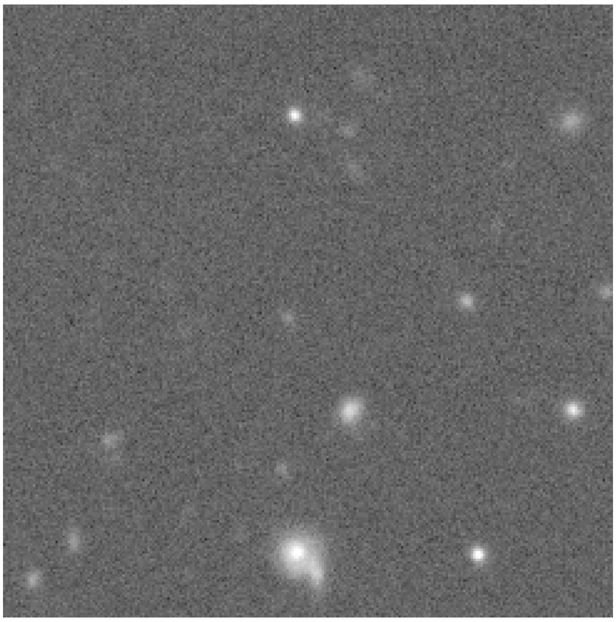

Figure 5: A J-band image of S02-032 taken with VLT/ISAAC on the 29th of Apr. The exposure time was about 380min. The central object is the SN, and the signal-to-noise ratio of the SN is about 13.

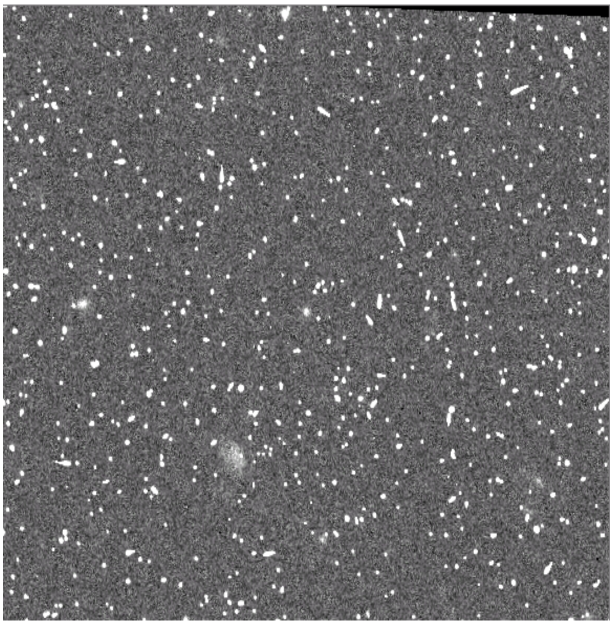

Figure 6: An single 720sec exposure image of S02-032 with HST/ACS. Since we haven't combined multiple exposures yet, there are many cosmic rays in the image, which will be removed by median filtering of multiple exposures.

(2) Refining and Testing SNe Ia as a Cosmology Tool.

We have shown (Perlmutter et al. 1997, 1999) that possible systematics in the measurement of Ω_M, Ω_Λ due to K-corrections, gravitational lensing amplification, and Malmquist bias, are quite small compared to the statistical error. Remaining sources of systematic uncertainty that we showed are unlikely, but possible, are SN Ia evolution and abnormal dust extinction. For this proposal, we have identified a series of refinements and tests that will "sharpen" this cosmological measurement tool, by addressing these two issues: as shown in Fig. 1, the form of the Hubble diagram at high-z expected for a Λ-dominated universe would be hard to mimic with systematic effects such as intergalactic gray dust or evolution in SN Ia peak magnitudes. Comparing the proposed high-signal-to-noise measurements of SNe Ia at $z \sim 0.85$ and at $z > 1$ will provide a direct test for such possible systematics. A further test, made possible with a set of well-measured high-z SNe, is to check for the increased dispersion in absolute magnitude expected from evolution or abnormal dust extinction. Optical color information in the rest frame is very important to carry out intensive tests. It is well known that the rest-frame U-B color of SNe has larger scatter than the B-V color, mainly because the rest-frame U-band is very sensitive to dust extinctions, small differences of explosion energy and phase, and so on. If we don't have J-band photometry, we have to use U-B color only for the SNe at $z > 1$, from which it is very hard to check the hypothesis of dust extinction or of evolution. Hence we propose to spend six nights for CISCO J-band photometry in order to get the rest-frame V-band image for $z \sim 1.2$ SNe. Though the required telescope time is not small, it is most straight forward to check if the B-V color systematically changes or not at the highest redshift we can carry out. We already have NIR photometry for some of SNe we found (Fig. 5), the six nights of CISCO will give us the first data set to see if the color systematics is seen at $z \sim 1.2$.

We will get I-band and z-band optical photometry with HST (telescope time allocated for three high-z SNe) and also with Suprime-Cam. We have two subsititution nights of Suprime-Cam from ToO (S01B-103), and we request using these two nights to carry out optical follow-up photometry with Suprime-Cam in addition to the "Big Project" observations. This will give us unique oppotunity to measure light curves and colors of medium redshift SNe at once, and will give us more data for the rest-frame B-V color at the intermediate redshift range.

Another possible interesting results from our proposal is to study how various the spectrum of distant SNe is. Though we haven't had any indications that the distant SNe Ia are different from nearby ones, we need many SN spectra to check the hypothesis that the evolution effect is not significant between $z = 0$ and $z = 1.2$. Four nights of FOCAS combined with telescope time of other 8-10m class telescopes enable us to get spectra of more than 15 distant SNe, if the weather condition is very good.

Deep Suprime-Cam imaging is ideal to give good candidates of this kind of study, since the candidates obtained with Suprime-Cam imaging can go well beyond $z = 1.2$. In fact, Suprime-Cam 2002 March-April search (S01B-103, S02A-174) found possible very distant SNe ($z > 1.3$). Fig. 7 shows a preliminary results of Keck/ESI spectroscopy of S02-035 which was found with Surpime-Cam. We also have a similar spectrum by VLT/FORS2 of another possiblly very distant SN (S02-001) found with Suprime-Cam, whose neaby galaxy possibly has the redshift of $z = 1.42$. The magnitudes of the SN candidates are consistent if they are at those redshifts. Either can be the highest redshift SN spectrum in the world record, though we haven't concluded yet. But we are very much confident that Suprime-Cam is finding SNe with $z > 1.2$, and we are also confident that we can study distant SN spectra with less luminosity bias from the SN Suprime-Cam will find.

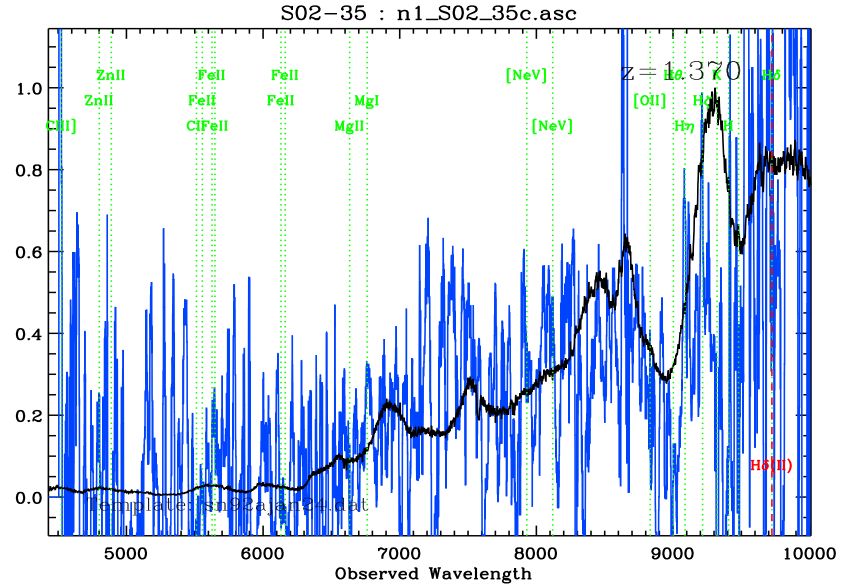

Figure 7: A preliminary spectrum of S02-035 taken with Keck/ESI. The exposure time was about 2 hours. The spectrum is consistent with SN Ia at $z = 1.37$.

(3) Roles of the Co-Investigators.

Mamoru Doi, the PI of the proposal, makes the whole schedules, carries out observations of SUBARU, and does coordinations with other telescopes. Naoki Yasuda is in charge of finding SN candidates from Suprime-Cam images. He has successfully found more than 50 SN candidates with Suprime-Cam (GTO, S01B-103, S02A-174). He will also work on follow-up photometry with Suprime-Cam. Nobunari Kashikawa is in charge of FOCAS observations and analysis. He has successfully taken spectra of more than 10 SNe (S01A-079, S02A-174) including three with $z > 1$. Kentaro Motohara was the support scientist of CISCO/OHS. Though CISCO hasn't tried follow-up photometry of distant SNe yet, he has enough experiences to carry out deep imaging with CISCO. Ken Nomoto is the the leader of the most powerful theoretical group of SNe in the world. His presense enables us to interprete the observational results very quickly, especially if we find any indications of possibly new feature (e.g. spectral evolution) of SNe Ia. Tomoki Morokuma and possible a few other graduate students will help observations and analysis with the key persons above.

There are also several members from the the Supernova Cosmology Project (SCP) international collaboration. Saul Perlmutter is the PI of the SCP, and will be in charge of overall scheduling/observations of other telescopes including the HST and the Keck. Isobel Hook is the key person of the GEMINI observations. Christopher Lidman is in charge of VLT observations. Raynald Pain is in charge of CFHT observations which will give us back-up imaging for imaging search. Ariel Goobar supports determining observational plans and schedules with realistic simulations.

(4) Importance of S02B.

This semester is ideal to carry out comprehensive high-z SN studies since the Big Project (SXDF) will give us the unique oppotunity to use wide-field capabilities of Suprime-Cam to its fullest extent. Using Suprime-Cam with FOCAS and CISCO we will be able to carry out a large campaign of comprehensive SNe studies mainly with SUBARU. Especially CISCO J-band imaging will refine our evolution/dust checks on systematics.

The observations will be backed up with other telescopes on earth and in space (with HST and Keck time already allocated) . This coordinated effort takes advantage of participation in the SCP international collaboration. The SCP intend to focus on the search in this fall rather than in the coming spring because of the Big Project.

After this SN search campaign, we expect 8 or more SNe followed with HST (with 7 found with Suprime-Cam). Though currently there are two competitive teams (High-Z team and SCP) for the distant SN search and the cosmological expansion measurements, the SCP definitely leads the competition mainly because of intensive observations of SUBARU.

(5) Conclusion.

Using an intensive use of SUBARU (Suprime-Cam, FOCAS, and CISCO), we will be able to carry out comprehensive studies of distant SNe and measurements of expansion of the universe at $z \sim 1$. The primary result will be to increase the SN found and measured at $z > 0.85$, which reduce the error plot of the cosmological parameters on the $\Omega_M - \Omega_\Lambda$ plane significantly. The intensive checking of spectral evolution and the rest-frame B-V color can be done at the most highest redshift range.

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